From Elastic Scattering to Central Exclusive Production: Physics with Forward Protons at RHIC

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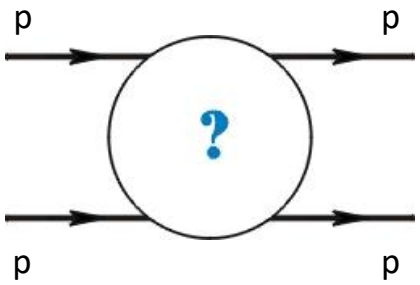
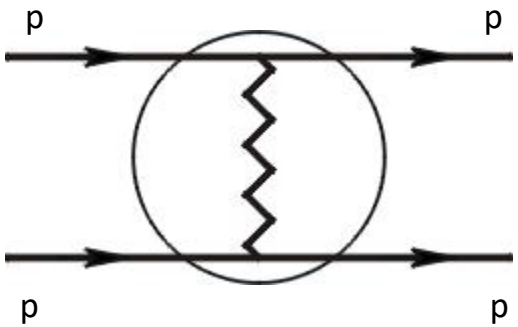
1. Processes with forward protons
2. Elastic Scattering
3. PP2PP experiment – Roman Pots and the first results
4. Move to the STAR experiment
5. Results at STAR
6. Summary of the program

Processes with Measured Forward Protons

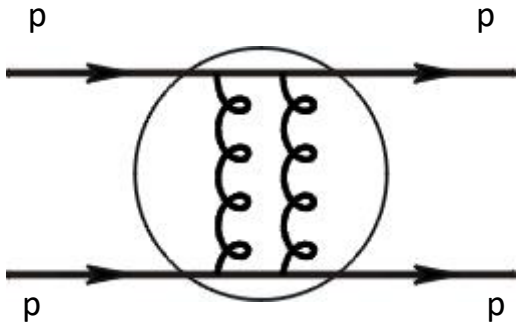


C=+1, C=−1

In t-channel it is an exchange with quantum numbers of vacuum



Non Pert. QCD – small mom. transf.

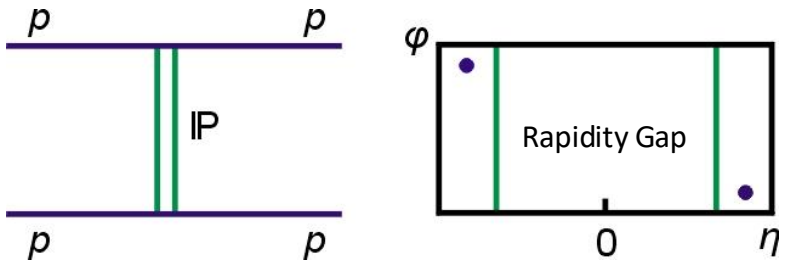


pQCD picture – large mom. transf.

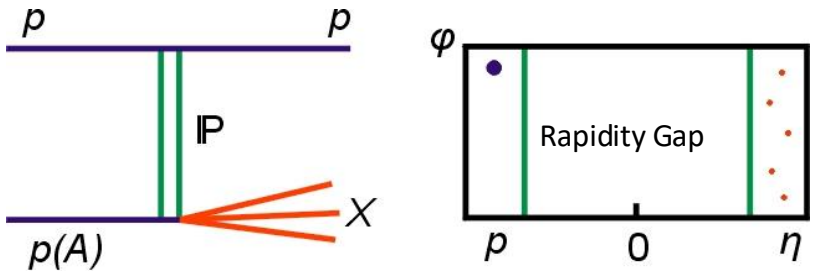
Domain of Regge theory – scattering amplitudes A are parameterized as function of (s,t) => A(s,t)

Domain of QCD Lagrangian – scattering amplitudes are calculated using the QCD Lagrangian.

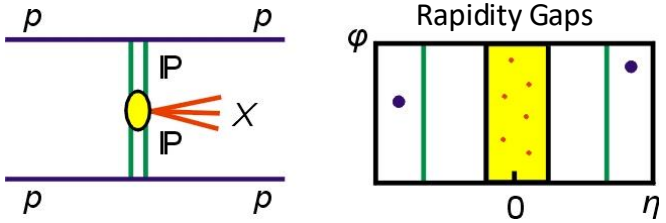
Few Examples: Elastic and Inelastic Processes



p + p → p + p elastic



p + p → p + X SDD

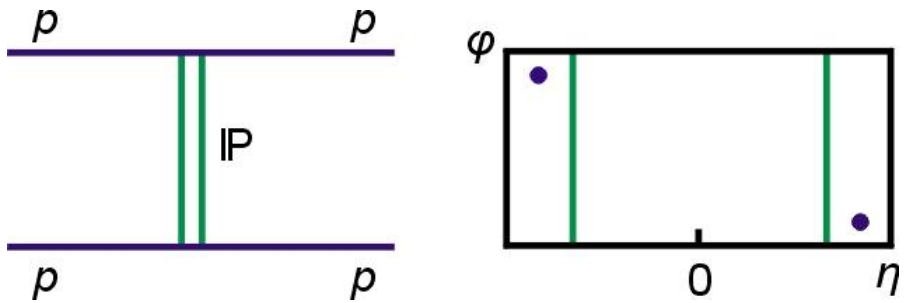


p + p → p + X + p
diffractive X= particles, glueballs

For each proton vertex one has
t four-momentum transfer
$\xi = \Delta p/p$
M_X invariant mass

In terms of QCD, Pomeron exchange consists of the exchange of a color singlet combination of gluons. Hence, triggering on forward protons at high (RHIC) energies enhances processes mediated by gluonic matter.

Proton – Proton Elastic Scattering



p + p → p + p

$$\frac{d\sigma}{dt} = \pi |f_c + f_h|^2$$

four-momentum transfer squared: $t = (p_1 - p_3)^2 \approx p^2\theta^2$

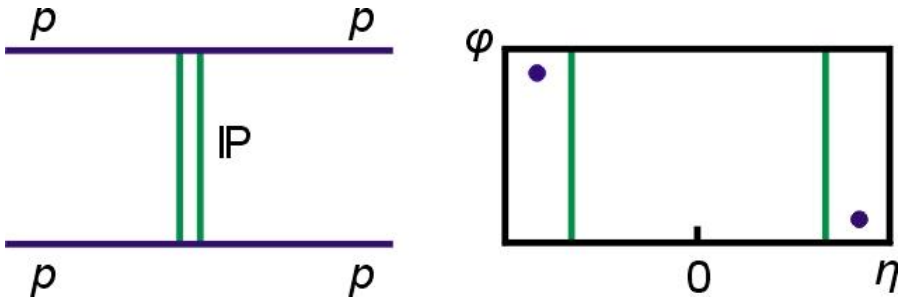
$$f_h = \left(\frac{\sigma_{tot}}{4\pi}\right)(\rho + i)\, e^{-\frac{1}{2}B|t|}$$

$$f_c = -\frac{2\alpha G_E^2(t)}{|t|} e^{i\alpha\phi}$$

$$\rho = \left.\frac{Re\ f_h}{Im\ f_h}\right|_{t=0}$$

$$\sigma_{tot}^2 = \left(\frac{16\pi\,(\hbar c)^2}{1+\rho^2}\right)\left.\frac{d\sigma_{el}^h}{dt}\right|_{t=0}$$

Spin Dependence in Proton – Proton Elastic Scattering



p + p → p + p

Five matrix elements

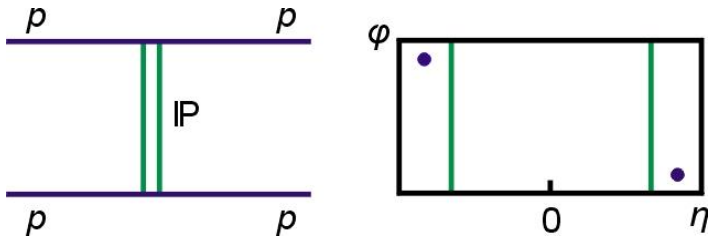
$$\phi_1(s,t) = \langle ++ | M | ++ \rangle \quad \text{non–flip}$$
$$\phi_2(s,t) = \langle ++ | M | -- \rangle \quad \text{double spin flip}$$
$$\phi_3(s,t) = \langle +- | M | +- \rangle \quad \text{non–flip}$$
$$\phi_4(s,t) = \langle +- | M | -+ \rangle \quad \text{double spin flip}$$
$$\phi_5(s,t) = \langle ++ | M | +- \rangle \quad \text{single spin flip}$$

$$\phi_i(s,t) = \phi_i^{EM}(s,t) + \phi_i^{HAD}(s,t)$$

$$\frac{d\sigma}{dt} = \frac{2\pi}{s^2}\left\{ |\phi_1|^2 + |\phi_2|^2 + |\phi_3|^2 + |\phi_4|^2 + 4|\phi_5|^2 \right\}$$

$$A_N(s,t)\frac{d\sigma}{dt} = \frac{-4\pi}{s^2}\,\mathrm{Im}\left\{ \phi_5^*(\phi_1 + \phi_2 + \phi_3 - \phi_4) \right\}$$

How it All Started: Elastic Scattering at the Time of the Proposal



p + p → p + p

four-momentum transfer squared: $t = (p_1 - p_3)^2 \approx p^2\theta^2$

Highest energy at that time:

pp: 63 GeV (ISR)

$p\bar{p}$: 1.8 TeV (Tevatron)

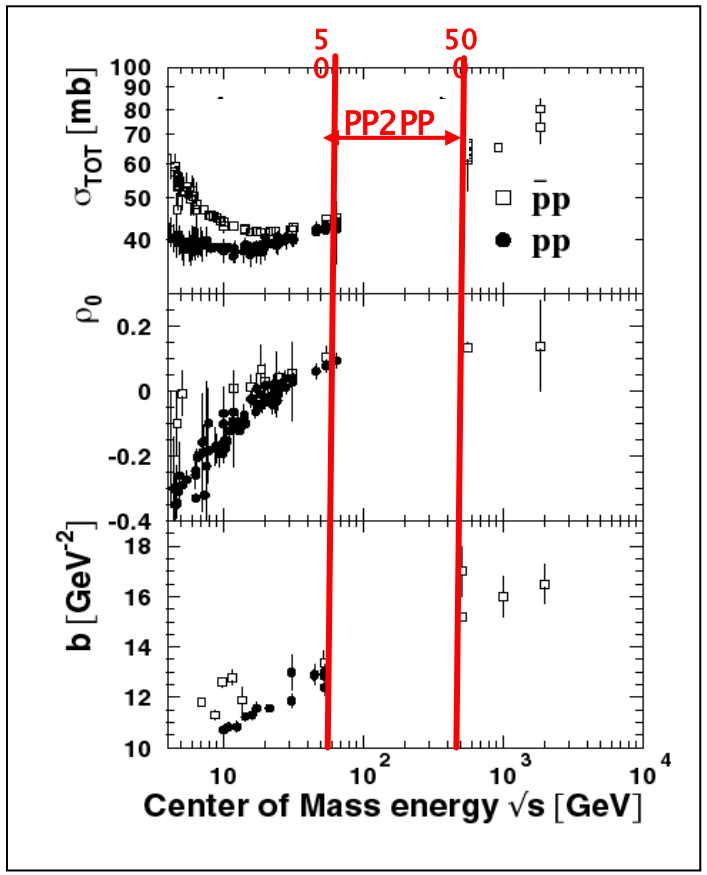
pp2pp energy range:

50 GeV ≤ $\sqrt{s}$ ≤ 500 GeV

$$\rho = \left.\frac{Re\, f_h}{Im\, f_h}\right|_{t=0}$$

$$\sigma_{tot}^2 = \left(\frac{16\pi\,(\hbar c)^2}{1+\rho^2}\right)\left.\frac{d\sigma_{el}^h}{dt}\right|_{t=0}$$

$$f_h = \left(\frac{\sigma_{tot}}{4\pi}\right)(\rho + i)\, e^{-\frac{1}{2}B|t|}$$



At the time of the proposal there was anomalous value ρ = 0.24 measured by UA4 experiment at $\sqrt{s} = 540$ GeV

RHIC: Heavy Ion and Polarized Proton – Proton Collider

Four HI experiments and one dedicated pp experiment

The Collaboration: LOI #1 at RHIC

TOTAL and ELASTIC pp CROSS SECTIONS AT RHIC

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University of Rome, Italy

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INFN-Trieste, Italy

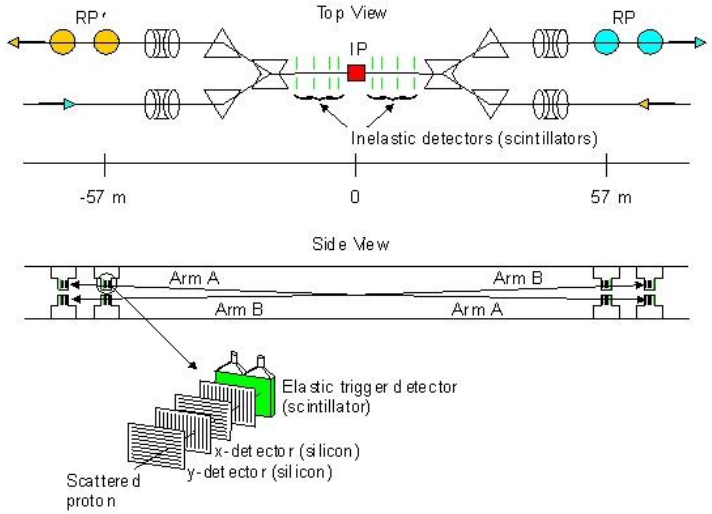
*spokesperson

Abstract

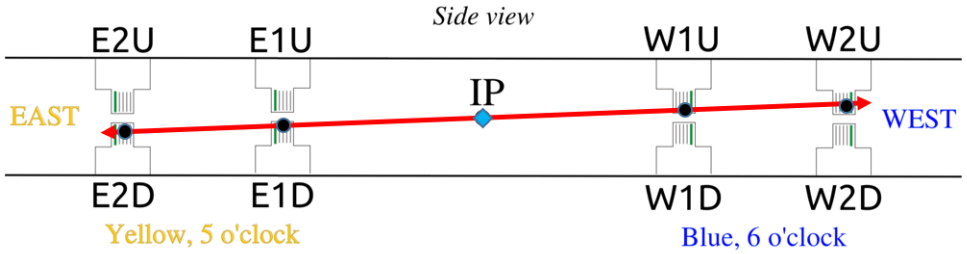
We are proposing to study proton-proton (pp) elastic scattering scattering at $\sqrt{s} = 500$ GeV. The lattice configuration and the angular coverage of the detector will allow the simultaneous study of all three regions that characterize elastic scattering, namely the Coulomb dominated region, the Coulomb-hadronic interference region and the hadronic dominated region, for four momentum transfer t in the range $0.0005 < t < 0.12 GeV/c^2$. The case for the large t up to $6 GeV/c^2$ is also presented. Application to the case of polarized beams is also discussed.

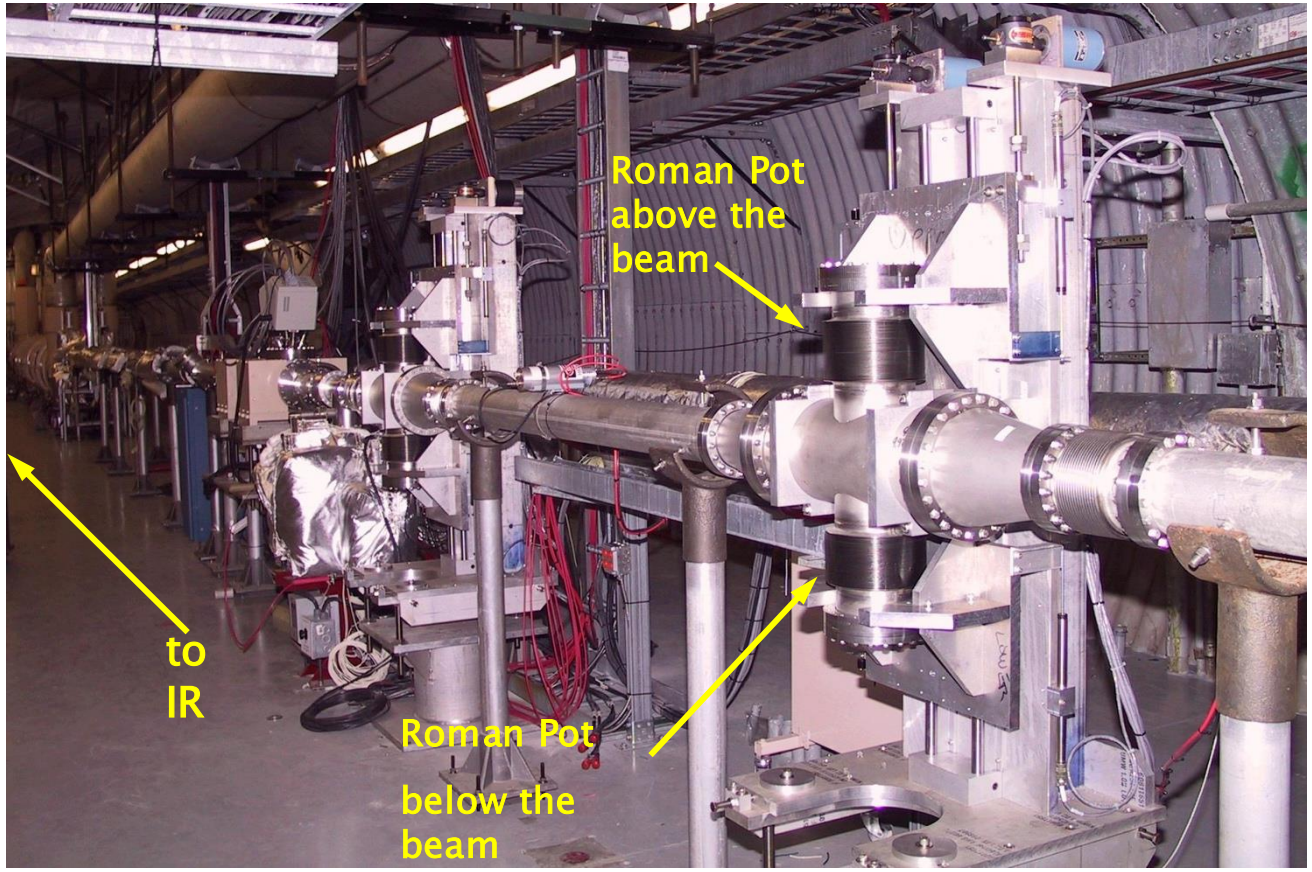
- We had very smart and competent people who were attracted to a small experiment at a world class facility – this was crucial.
- We were also lucky to get support from many people not on PP2PP but who were interested enough to find time to solve many technical problems and participate in construction – also very crucial.
- They were STAR collaborators at the time (Dave Lynn, Tonko Ljubicic, Jeff Landgraf, Bob Soja), also from BRAHMS (Bob Scheetz, John Hammond) and PHENIX (Steve Booze) and many at C-AD.

The PP2PP Experimental Setup at RHIC



$$\vec{p}_1 = -\vec{p}_2 \Rightarrow (\Theta_x^1, \Theta_y^1) = (-\Theta_x^2, -\Theta_y^2)$$



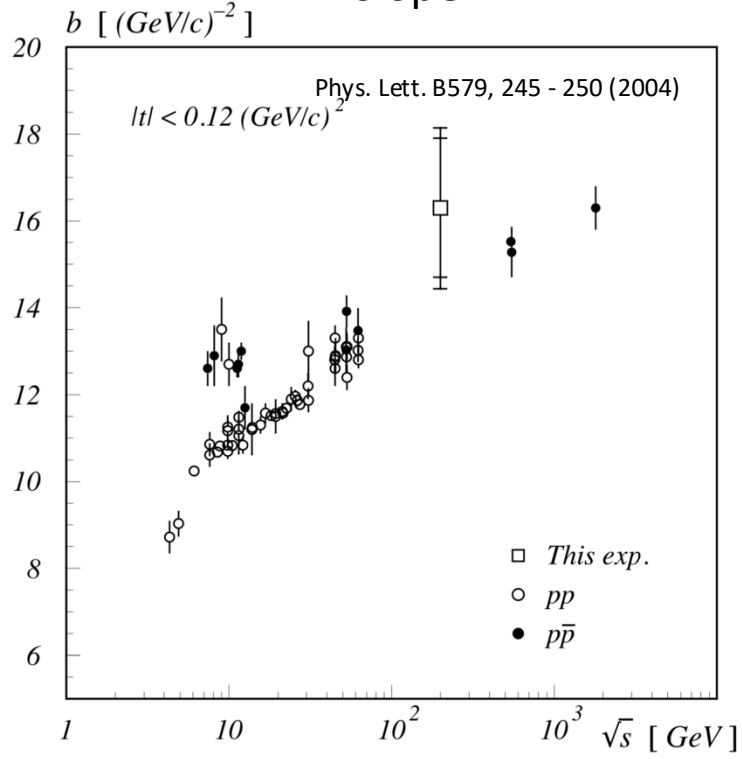


Protons scatter at small angles and stay inside the beampipe.
Hence, they follow accelerator magnets.

Results with PP2PP

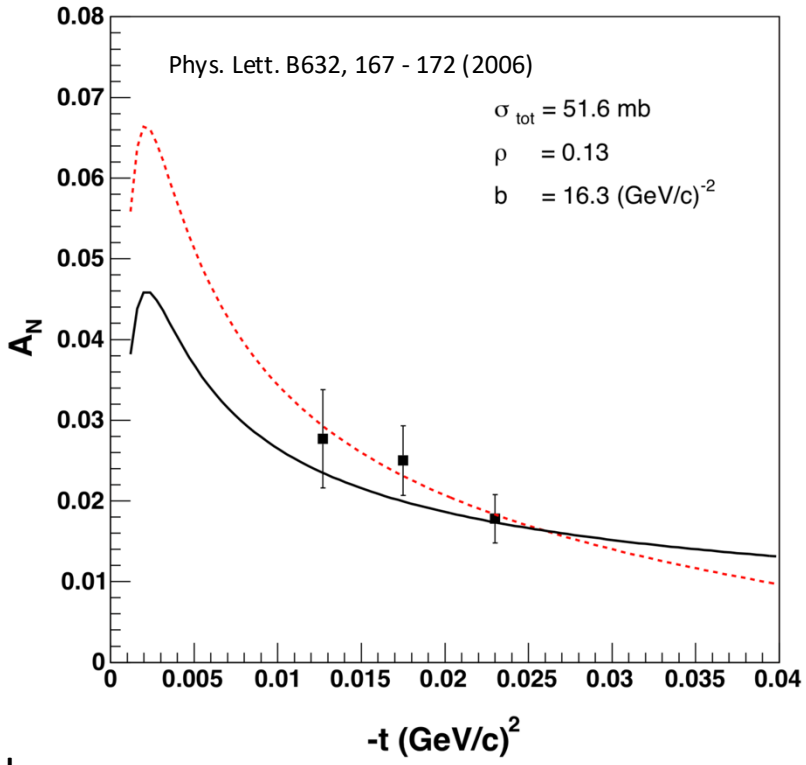
Results from PP2PP at small -t

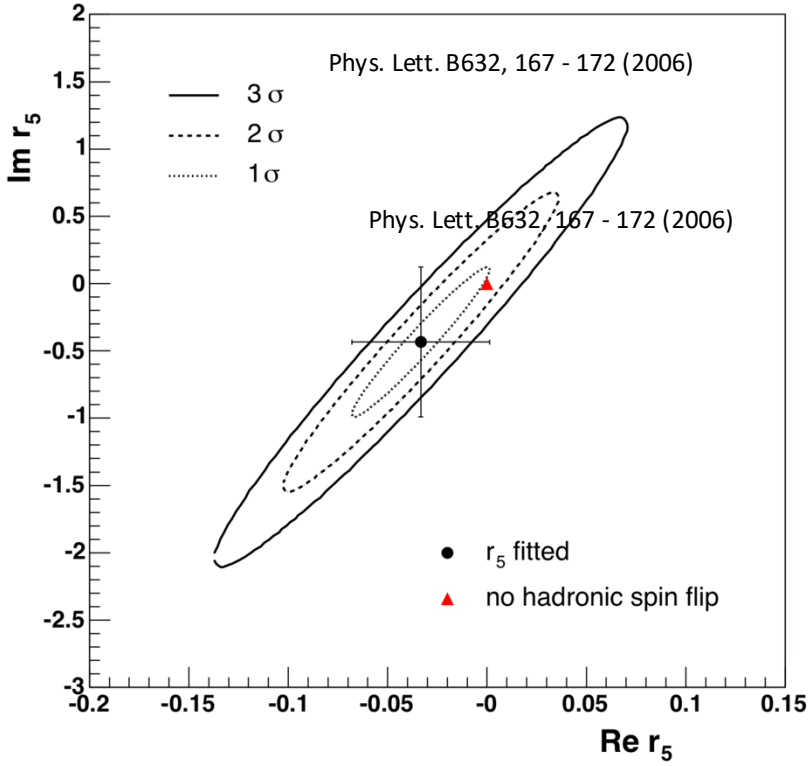
B- Slope



Nuclear Slope B – consistent with world data (relatively large uncertainty due to limited running time)

Single spin asymmetry A_N





Single spin analyzing power A_N => Hadronic spin-flip (r_5)
r_5 consistent with zero

PP2PP

Results from PP2PP ctnd

TABLE I: Double spin asymmetries A_{NN}, A_{SS}, $(A_{NN} + A_{SS})/2$ and $(A_{NN} - A_{SS})/2$ for the t-interval $0.010 \leq -t \leq 0.030$ $(\mathrm{GeV/c})^2$ at $< -t >= 0.0185$ $(\mathrm{GeV/c})^2$.

	A_{NN}	A_{SS}	$(A_{NN} + A_{SS})/2$	$(A_{NN} - A_{SS})/2$
$Asym$	0.0298	0.0035	0.0167	0.0131
$\Delta Asym$ (stat.+norm.)	$\pm$0.0166	$\pm$0.0081	$\pm$0.0091	$\pm$0.0096
$\Delta Asym$ (syst.)	$\pm$0.0045	$\pm$0.0031	$\pm$0.0034	$\pm$0.0072
$\Delta Asym$ due to $\Delta(P_Y \cdot P_B)$	$\pm$32.3 %			

Phys. Lett. B647, 98 - 103 (2007)

Double spin asymmetry A_{NN} consistent with zero

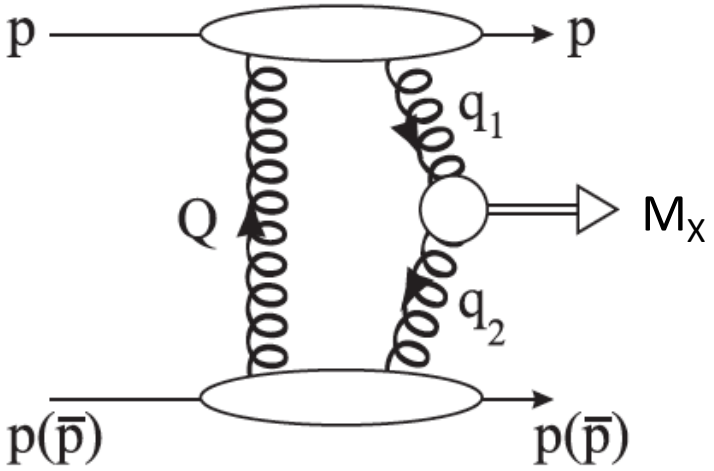
Three papers published in PLB

Then the 2006 RHIC funding crisis came

In 2005, despite very good progress and three publications being worked on, the PP2PP experiment was cancelled by BNL ALD because of 2006 budget constraints, where there was no money to run RHIC.
Let alone continue PP2PP.

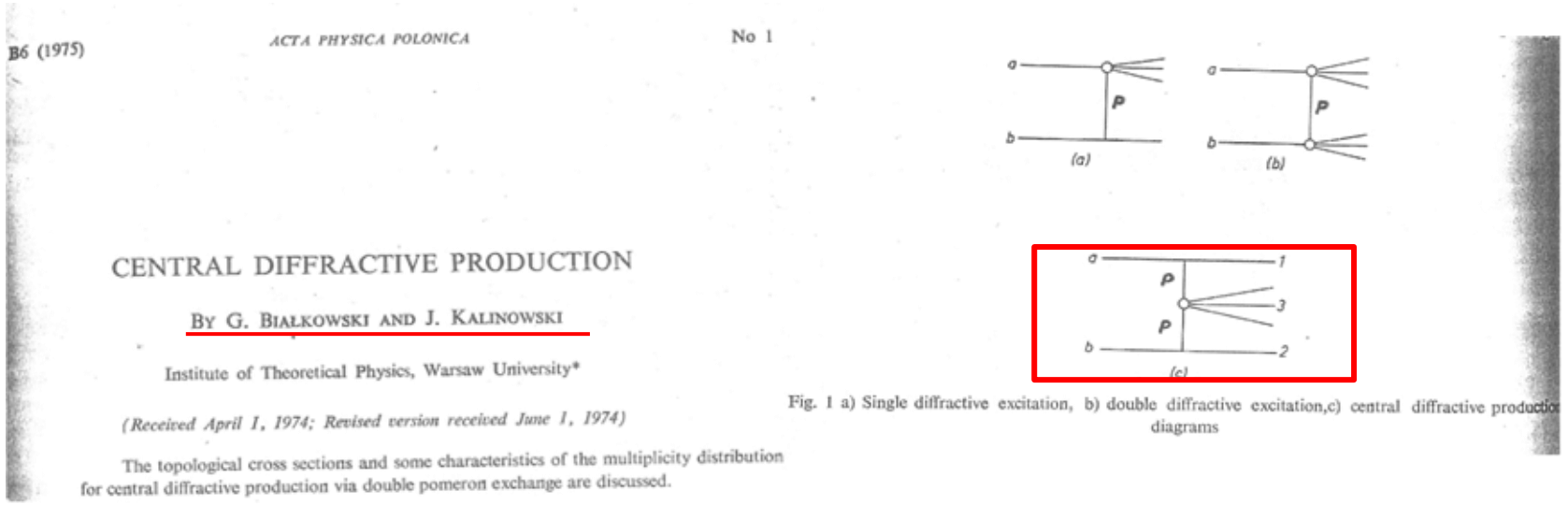
This is when I learned the importance of this cartoon.

Central Production – Short Summary



- Colliding protons interact via a color singlet exchange and remain intact after the interaction.
- In the collider experiment those protons follow magnetic field of the accelerator and remain in the beam pipe.
- A system of mass M_X is produced, whose decay products are present in the central detector region.
- Triggering on forward protons assures rapidity gap (modulo) soft rescattering processes, which fill the gap. Such effect is quantified by gap survival probability factor.

This Topic Has a Long History



B6 (1975) ACTA PHYSICA POLONICA No 1

CENTRAL DIFFRACTIVE PRODUCTION

By G. Białkowski and J. Kalinowski

Institute of Theoretical Physics, Warsaw University*

(Received April 1, 1974; Revised version received June 1, 1974)

The topological cross sections and some characteristics of the multiplicity distribution for central diffractive production via double pomeron exchange are discussed.

Fig. 1 a) Single diffractive excitation, b) double diffractive excitation,c) central diffractive production diagrams

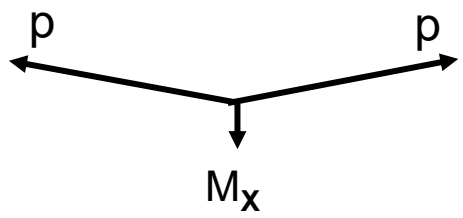
Most recent summary and history of Central Exclusive Production (CEP) in:

International Journal of Modern Physics A, Volume: 29, Number: 28 (10 November 2014), Central Exclusive Production in Hadron–Hadron Collisions; Guest Editors: M. Albrow, V. Khoze and C. Royon

Central Exclusive Production

In the Central Exclusive Production process there is a momentum balance between the central system M_X and the outgoing protons.

$M_X = \sqrt{\xi_1 \xi_2 s}$ - invariant mass



For each proton vertex one has

t four-momentum transfer

$\xi = \Delta p/p$

The massive system could form resonances. We expect that because of the constraints provided by the double Pomeron interaction, glueballs, hybrids, and other states coupling preferentially to gluons, will be produced with much reduced backgrounds compared to standard hadronic production processes.

Lattice QCD Glueball Spectrum – Most Shown Plot Here

Sparse spectrum!

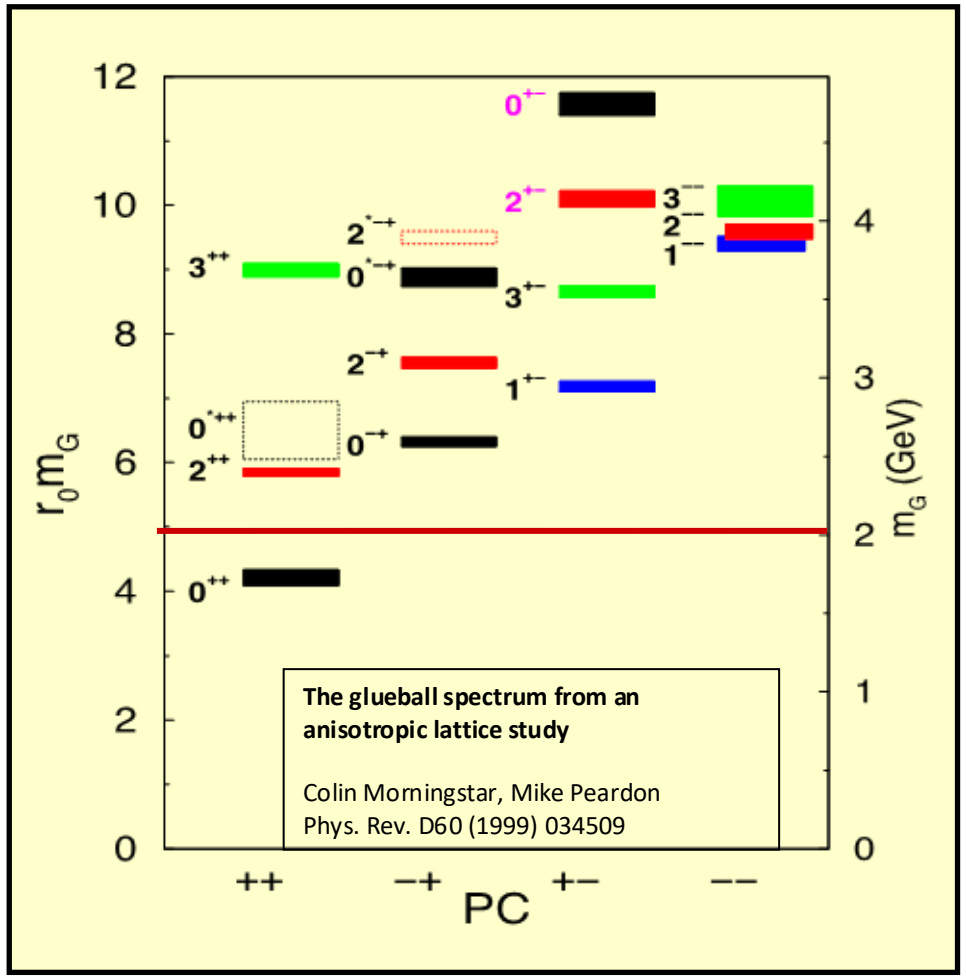
New I=0 mesons starting with

0^{++} 1.6 GeV

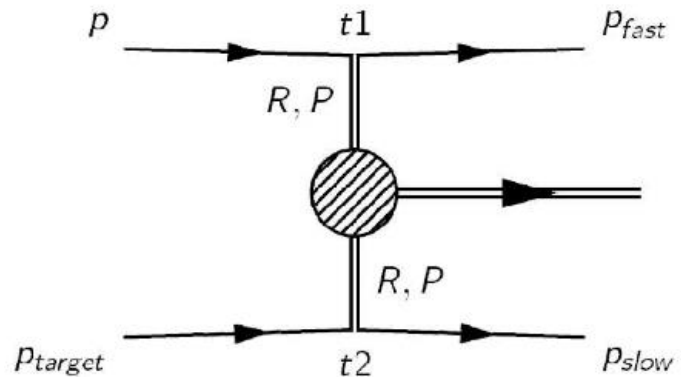
0^{-+} , 2^{++} 2.3 - 2.5 GeV

No **J^{PC}-exotic** glueballs until

2^{+-} at 4 GeV



COMPASS Experiment √s = 19 *GeV*



$\sigma_{RR} \sim s^2$

$\sigma_{RP} \sim s^1$

$\sigma_{PP} \sim$ const. or s^{α} where $\alpha \sim (0.1)$

http://arxiv.org/pdf/1402.2170v1.pdf

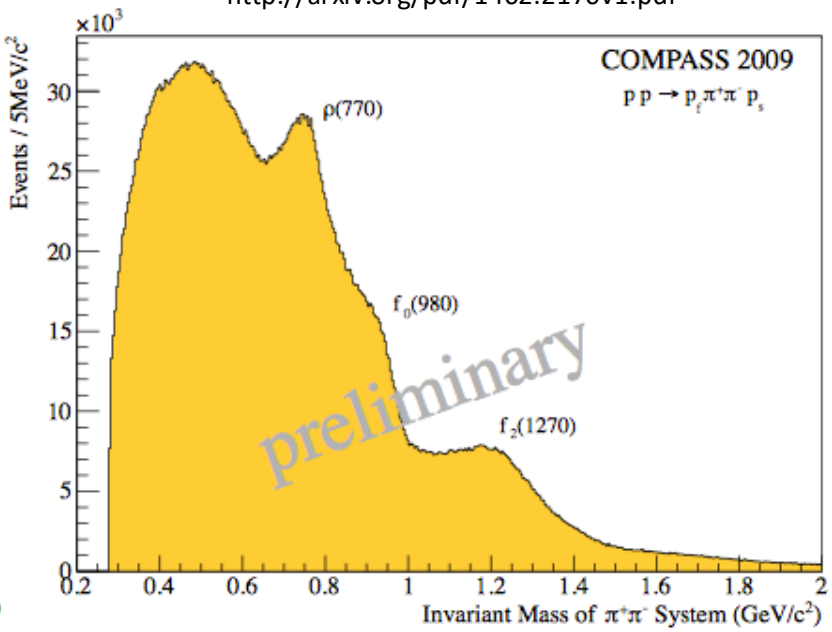


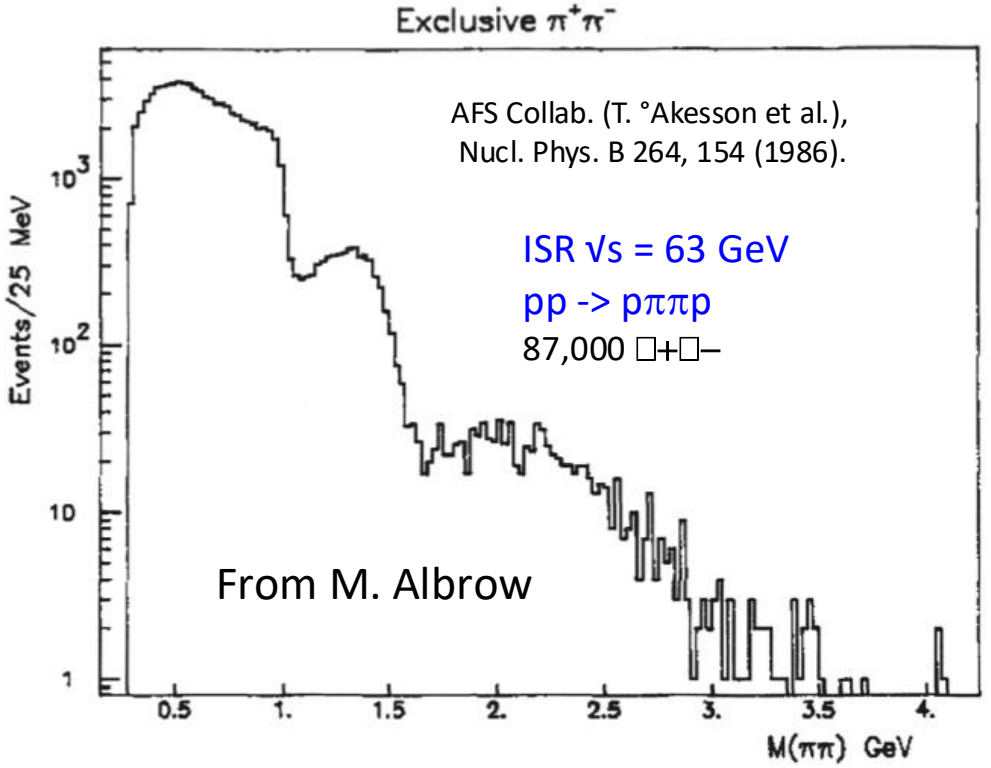
Figure 3: $\pi^+\pi^-$ system.

Figure 3 shows the invariant mass spectrum of the central $\pi^+\pi^-$ system, where the $\rho(770)$, the $f_2(1270)$, and the sharp drop in intensity in the vicinity of the $f_0(980)$ resonance can be observed as dominant features. Since the $\rho(770)$ cannot be produced via double-Pomeron exchange (DPE), contributions from other production mechanisms are evidently non-negligible at $\sqrt{s} = 19\,\mathrm{GeV}/c^2$.

Need to go to higher energies!

Experiment at the ISR

Note ISR is the name of the first world pp collider (at CERN), it is not Initial State Radiation

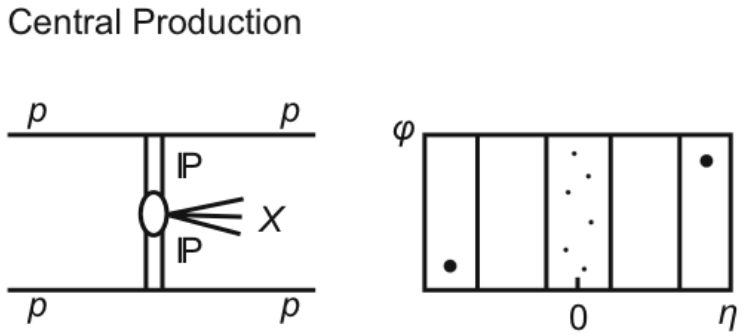


No sign of ρ(770) so Pomeron-Regge(ρ*) exchange absent.

proton $x_F > 0.95$, protons non-colinear (UP*UP or DN*DN)

$-t = [0.01, 0.06]$ $(GeV/c)^2$, $|y(\pi\pi)| < 1$

Glueball Central Production at RHIC



Method is complementary to:

- GLUEX experiment
- PANDA experiment
- BES
- COMPASS

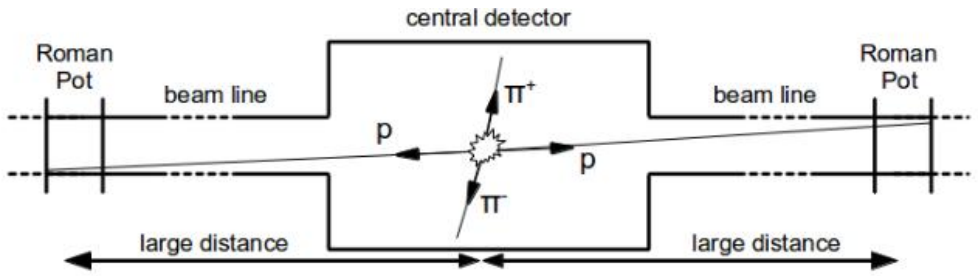
The idea that the production of glueballs is enhanced in the central region in the process pp → pM_Xp was first proposed by F.Close and was demonstrated by WA102 expt.

The pattern of resonances produced in central region depends on:

$$dP_T = |\overrightarrow{k_{T1}} - \overrightarrow{k_{T2}}|$$

When $dP_T \geq \Lambda_{QCD}$ $q\bar{q}$ states are prominent and when dP_T is small the surviving resonances are expected to include glueball candidates.

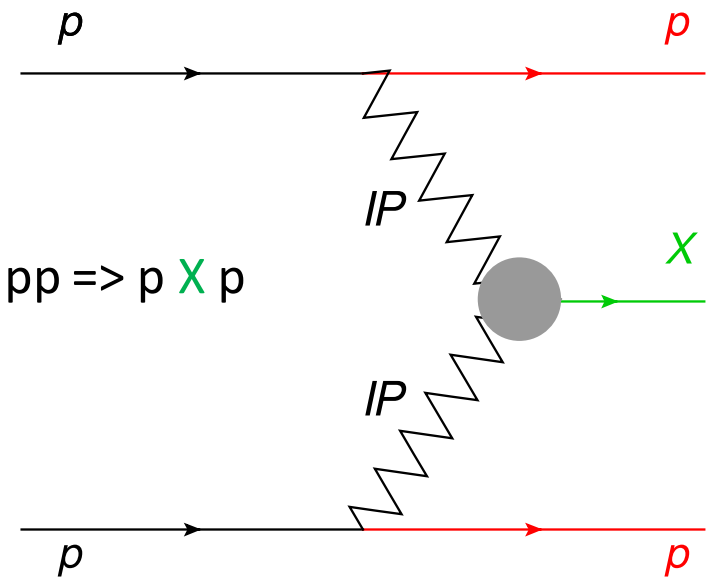
Let's Try to Propose an Experiment at pp Collider

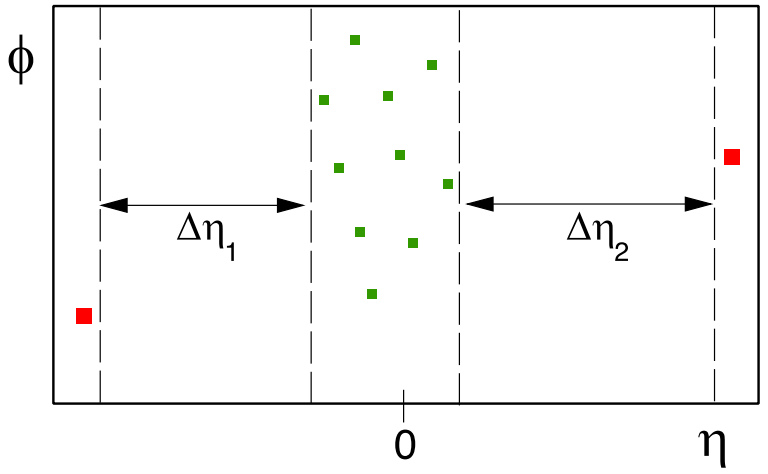


1. Physics topic: particle and resonance production of light mass systems (glueballs) in CEP.
2. How to implement: need to measure:
   - central system – to identify (charged) particles (π, K, p);
   - forward protons – to assure CEP.
3. Need to go to a committee for approval, describe expected performance, obtain a grant.

The latter is the hardest step!

Proposal to STAR to Measure Central Exclusive Production (CEP) and Continue Elastic Scattering Program



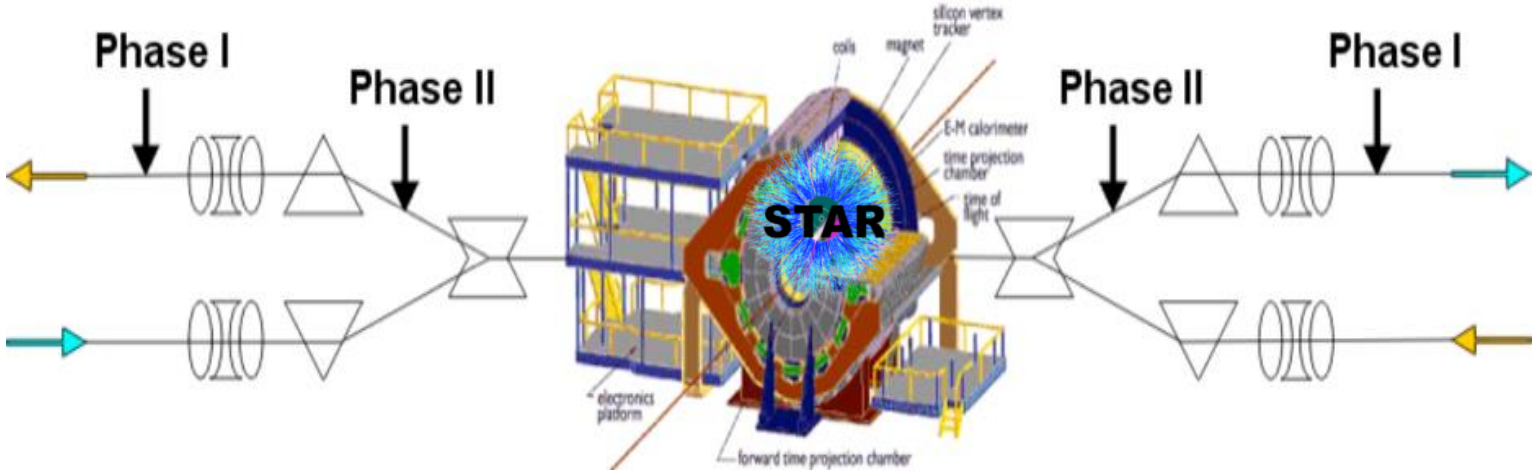


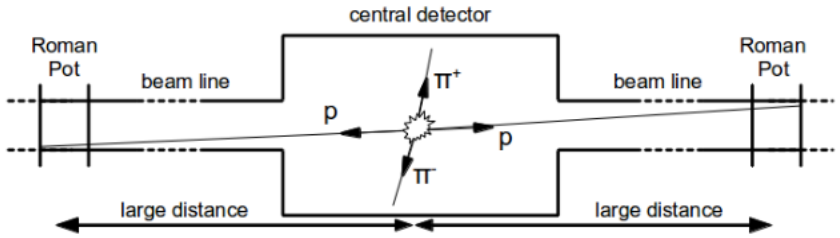
Exclusive means that all particles in the final state are measured

Joining STAR in 2006: Physics with Measured Forward Protons

Roman Pots of PP2PP and STAR

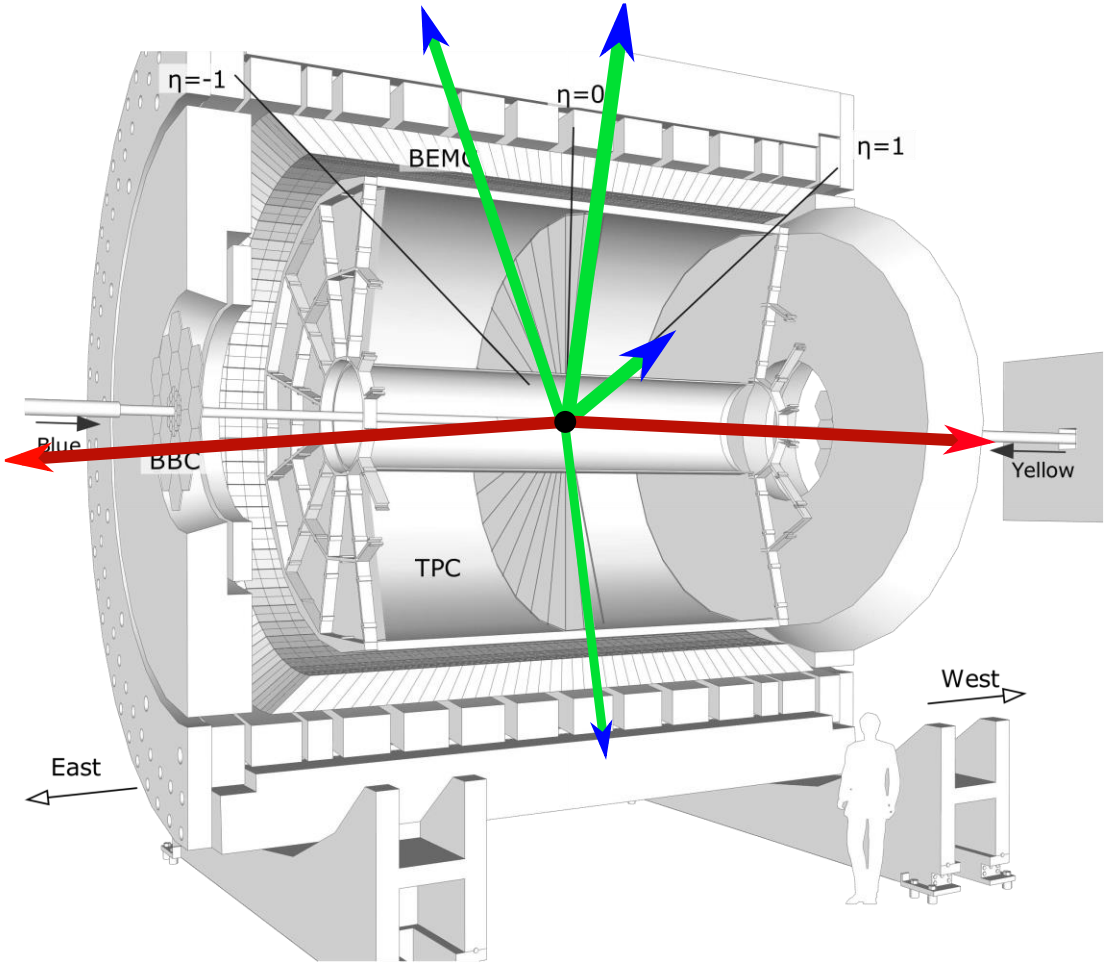
(Larry McLerran Compromise: Use existing equipment, NO dedicated Experiment)



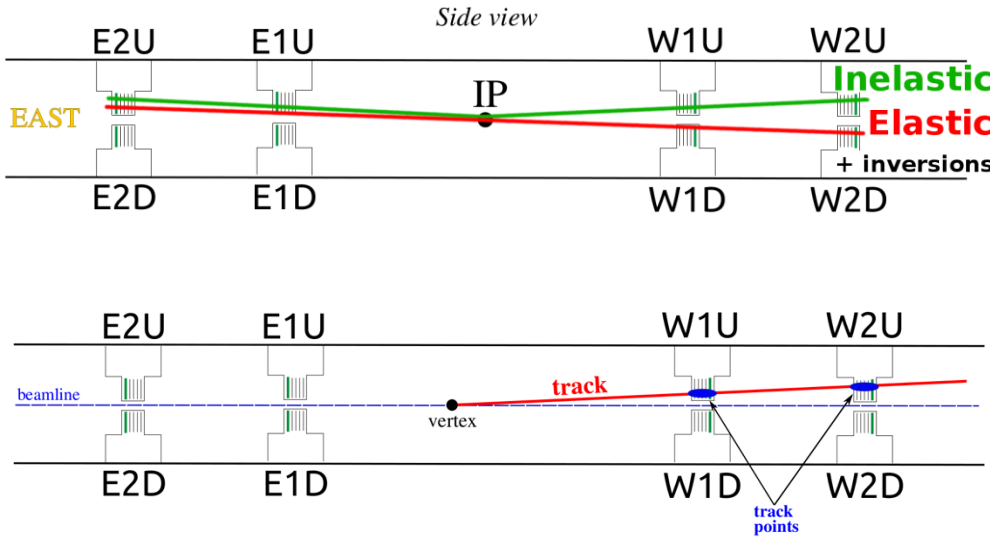


1. Elastic Scattering and its spin dependence
2. Central Exclusive Production
3. Particle Production in SDD and CP
4. Heavy Flavor J/ψ

CEP at STAR: Combine Excellent PID of STAR with Forward Proton Measurement of PP2PP



Roman Pots



Roman Pot setup moved to STAR and PP2PP became part of the STAR experiment. Elastic scattering is also part of the physics program.

Results with STAR

Single spin A_N asymmetry result

Matrix elements

$\phi_1(s,t) = \langle ++ | M | ++ \rangle$ non–flip

$\phi_2(s,t) = \langle ++ | M | -- \rangle$ double spin flip

$\phi_3(s,t) = \langle +- | M | +- \rangle$ non–flip

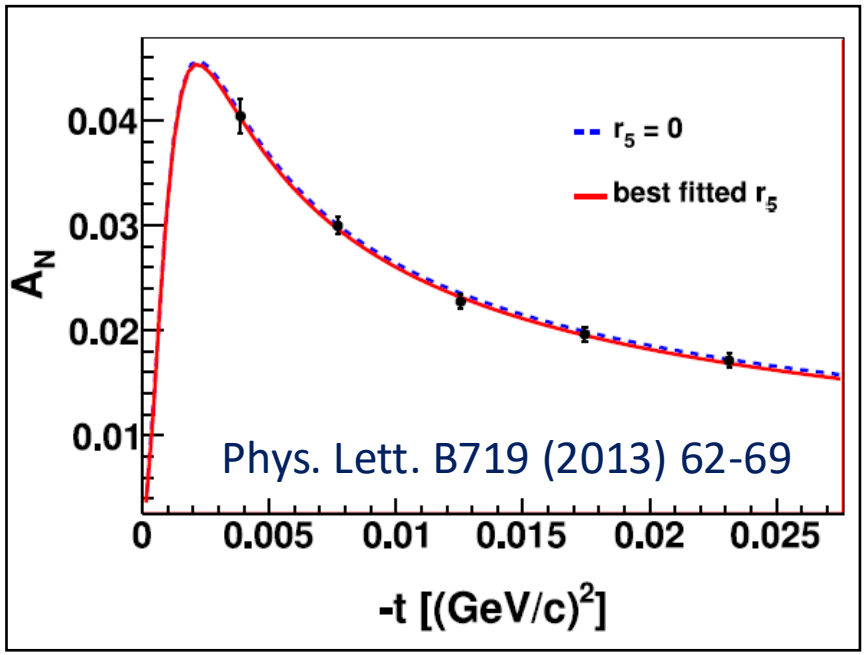
$\phi_4(s,t) = \langle +- | M | -+ \rangle$ double spin flip

$\phi_5(s,t) = \langle ++ | M | +- \rangle$ single spin flip

$$\phi_i(s,t) = \phi_i^{EM}(s,t) + \phi_i^{HAD}(s,t)$$

$$\frac{d\sigma}{dt} = \frac{2\pi}{s^2}\left\{ |\phi_1|^2 + |\phi_2|^2 + |\phi_3|^2 + |\phi_4|^2 + 4|\phi_5|^2 \right\}$$

$$A_N(s,t)\frac{d\sigma}{dt} = \frac{-4\pi}{s^2}\,\mathrm{Im}\left\{ \phi_5^*(\phi_1 + \phi_2 + \phi_3 - \phi_4) \right\}$$



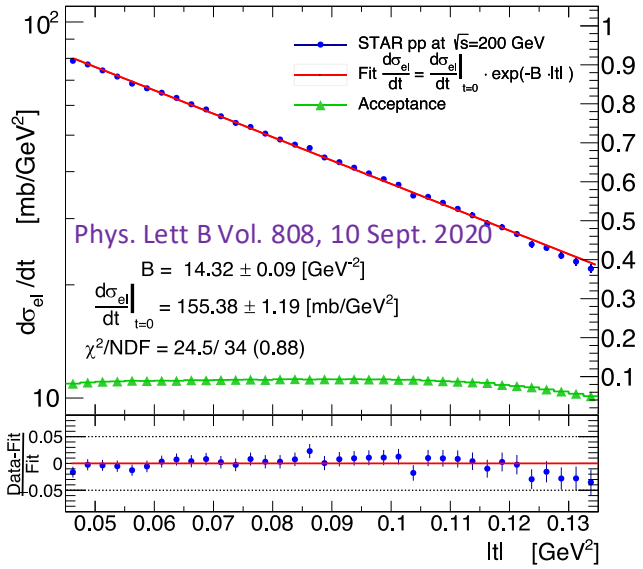
Re r_5 = 0.0017 +-0.0017 (stat.) +-0.061 (syst.)
Im r_5 = 0.007 +-0.03 (stat.) +- 0.049 (syst.)

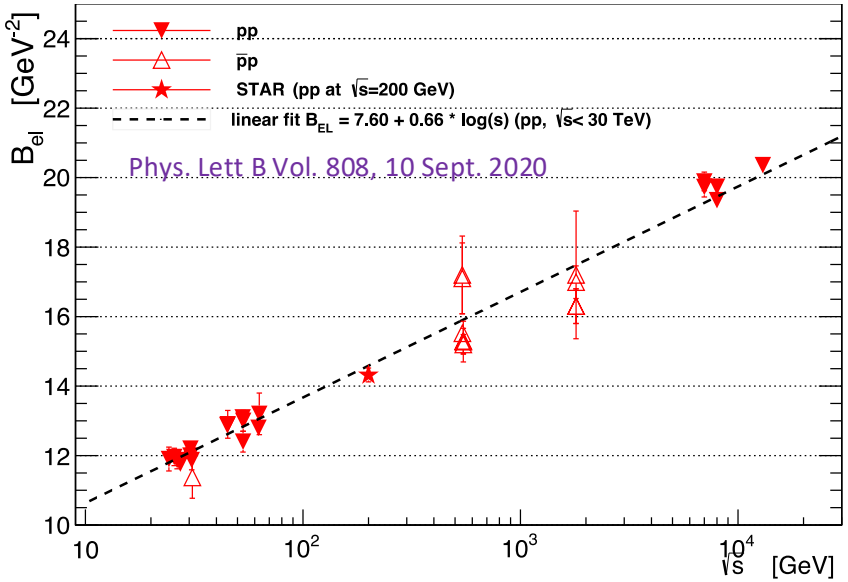
Pomeron spin-flip is consistent with zero

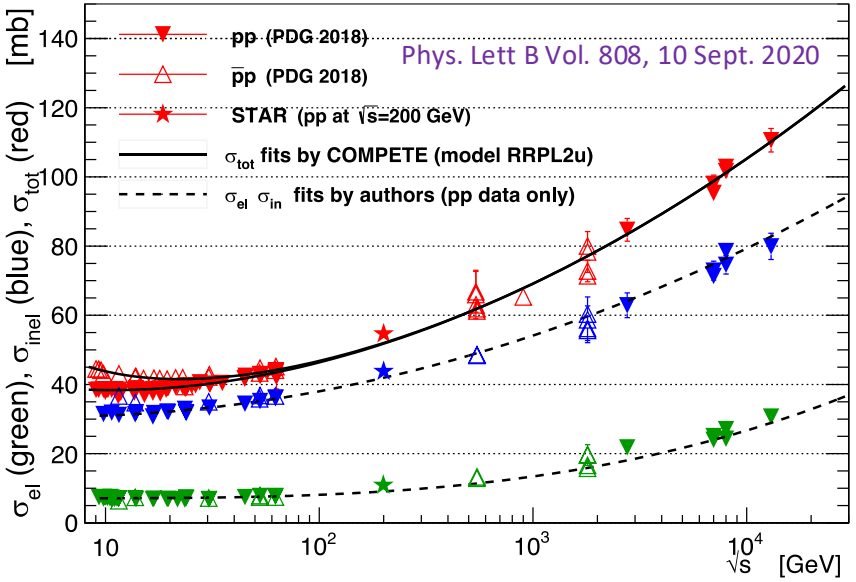
Results on Elastic scattering: σ_{tot} and B-slope at $\sqrt{s} = 200$ GeV

Use optical theorem to obtain σ_{tot}

$$\sigma_{tot}^2 = \left(\frac{16\pi\,(\hbar c)^2}{1+\rho^2}\right)\left.\frac{d\sigma_{el}^h}{dt}\right|_{t=0}$$

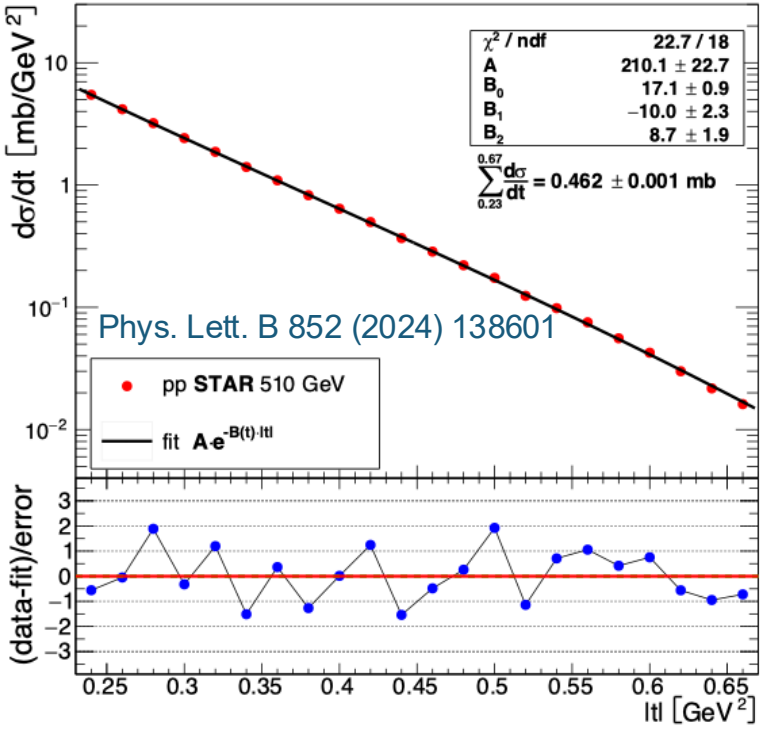


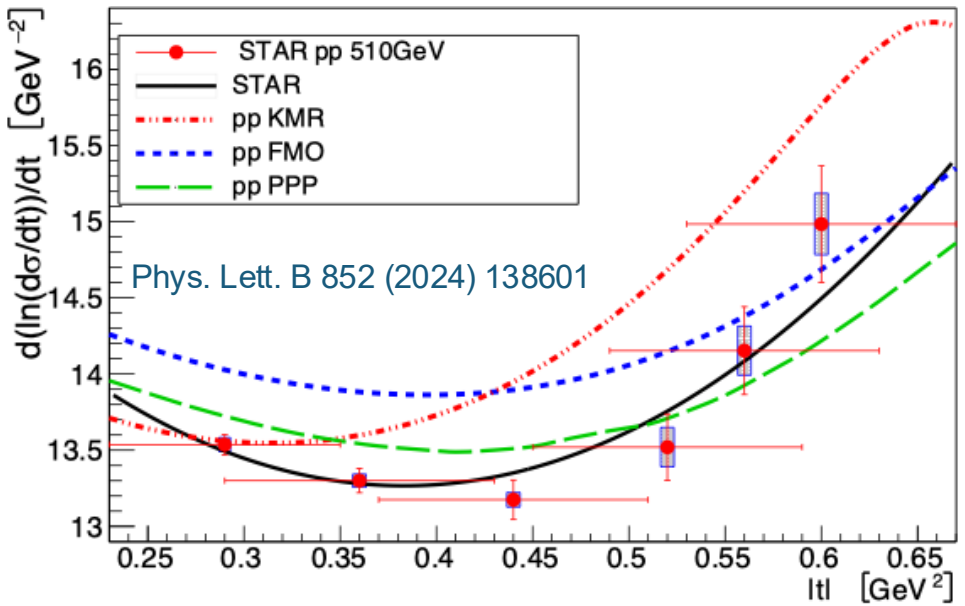




1. STAR obtained results on total, elastic and inelastic cross section in proton-proton collisions at $\sqrt{s} = 200$ GeV.
2. The results are within 2σ of the World data – fits do not include STAR data points.
3. This measurement ”fills” the gap between results from CERN ISR (62 GeV) and TeV energies at the LHC.

Results on Elastic scattering: B-slope at $\sqrt{s} = 510$ GeV





1.B(t) was found to be a second order polynomial

2.The curvature found to be most consistent with the PPP model

Exclusivity is determined by p_T^{miss}

$$p_{\mathrm{T}}^{\mathrm{miss}} := \left| \left(\vec{p}_{p^{\mathrm{E}}} + \vec{p}_{h^+} + \vec{p}_{h^-} + \vec{p}_{p^{\mathrm{W}}} \right)_{\mathrm{T}} \right|$$

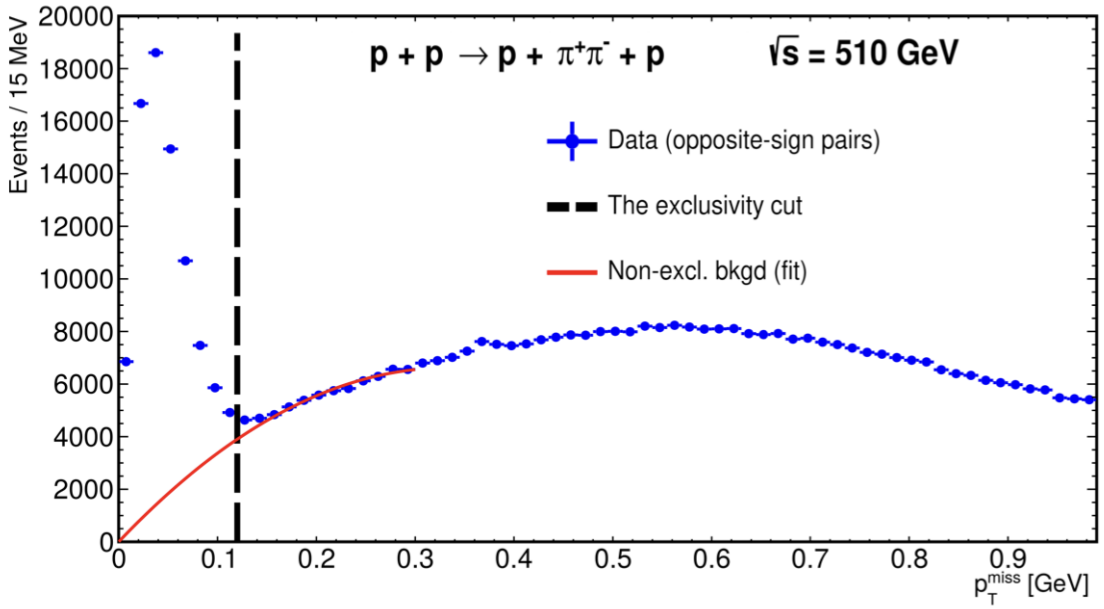
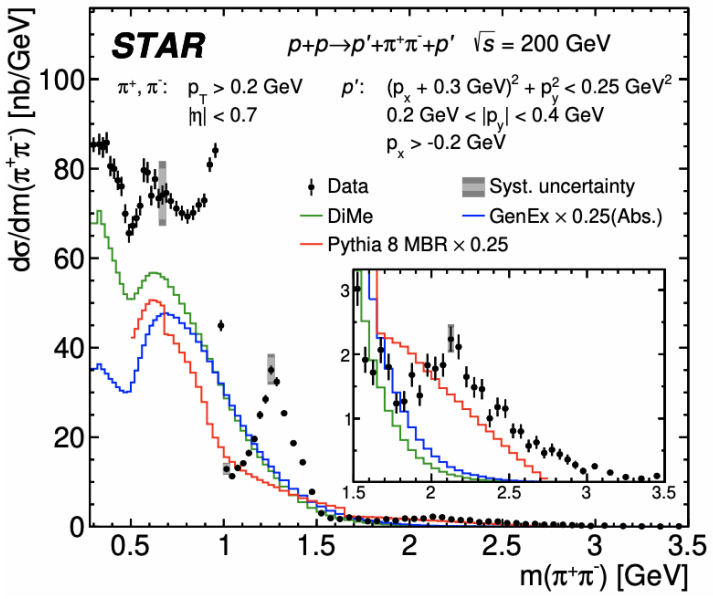
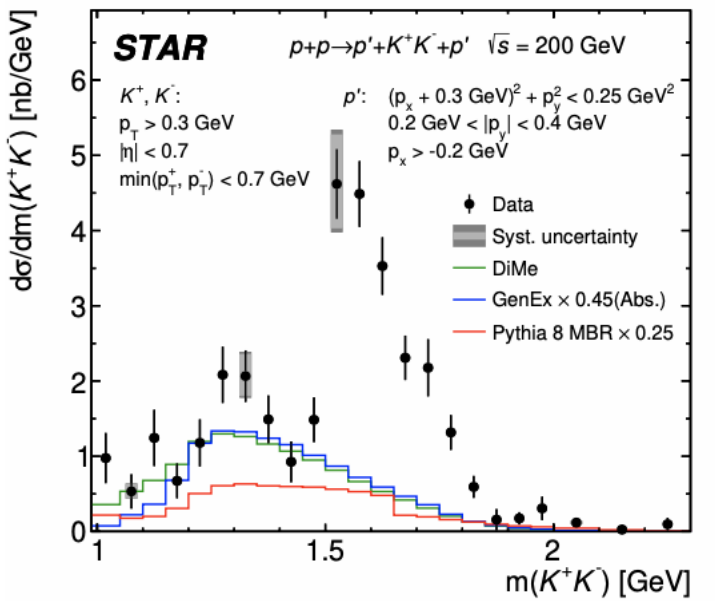


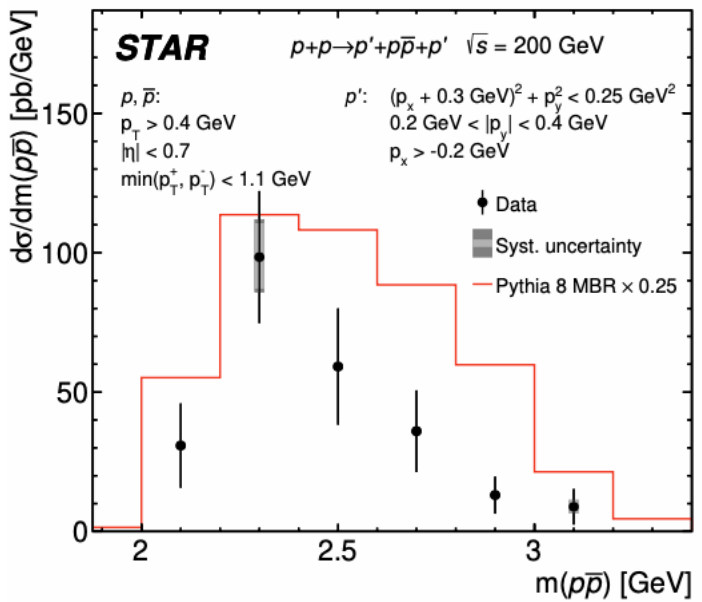
Figure 5. The distribution $p_{\mathrm{T}}^{\mathrm{miss}}$ for $\pi^+\pi^-$ CEP event candidates with the $p_{\mathrm{T}}^{\mathrm{miss}}$ cut illustrated by the black dashed line. The non-exclusive background is fitted using a second-degree polynomial with the constant term set to zero. The fit is depicted by the red line and projected into the signal region.

Results on CEP: $\pi^+\pi^-$, K^+K^-, $p\bar{p}$ production at $\sqrt{s}$ = 200 GeV

R. Sikora PhD thesis at AGH UST, *J. High Energy Phys.* **2020,** 178 (2020)



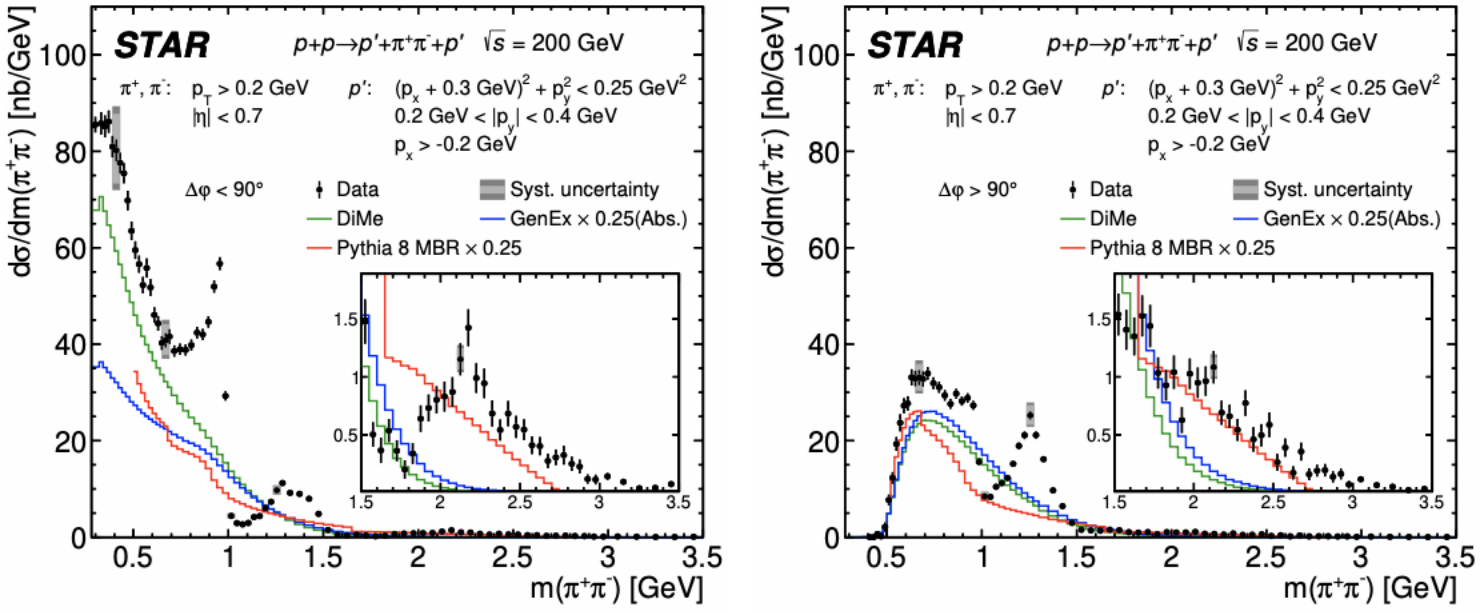




1. In $\pi^+\pi^-$ spectrum drop at f0(980), a peak at f2(1270) MeV and structure at about 2200 MeV , are observed.
2. Comparison with various continuum production models will help fine tune those models .

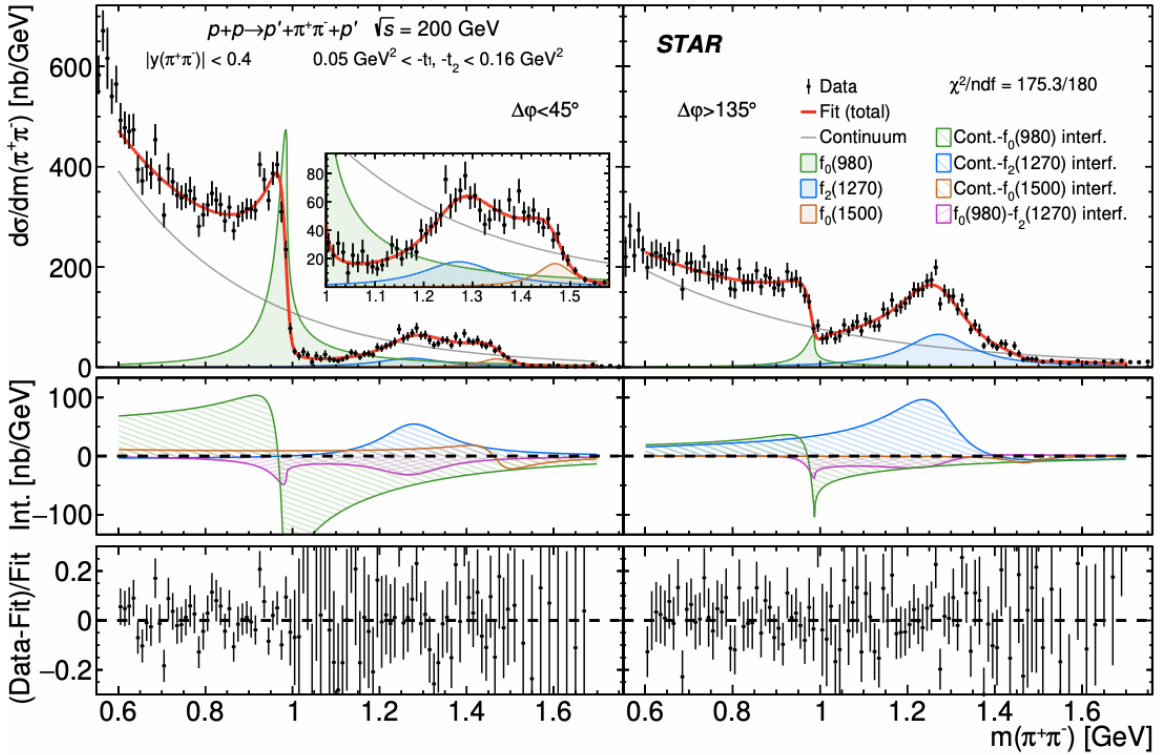
Results on CEP: $\pi^+\pi^-$ at $\sqrt{s}$ = 200 GeV in more detail $\Delta\phi$ dependence

R. Sikora PhD at AGH UST, *J. High Energy Phys.* **2020,** 178 (2020)



1. In the $\Delta\phi < 90^\circ$ range, the peak around the f2(1270) resonance in data is significantly suppressed.
2. Peak at f0(980) as well as possible resonances in the mass ranges 1.3 − 1.5 GeV and 2.2 − 2.3 GeV, are enhanced compared to the $\Delta\phi > 90^\circ$ range.
3. In the range $\Delta\phi < 90^\circ$, the DiMe model describes well both the normalization and the shape of the mass spectrum at m(π+π−) < 0.5 GeV.

Results on CEP: $\pi^+\pi^-$ in more detail mass spectrum interpretation



R. Sikora PhD at AGH UST,
J. High Energy Phys. **2020,** 178 (2020)

1. Two $\Delta\phi$ regions are examined.
2. The result of the fit is drawn with a solid red line. The squared amplitudes for the continuum and resonance production are drawn with lines of different colors.
3. The most significant interference terms are plotted in the middle panels, while the relative differences between each data point and the fitted model is shown in the bottom panels.

Comparison with GRANIITTI at $\sqrt{s} = 200$ GeV

M. Mieskolainen, Graniitti: Towards a Deep Learning-enhanced Monte Carlo Event Generator for High-energy Diffraction, Acta Phys. Pol. B Proc. Suppl. 16 (2023) 6

Mass spectra $\sqrt{s} = 200$ GeV Kinematic variables

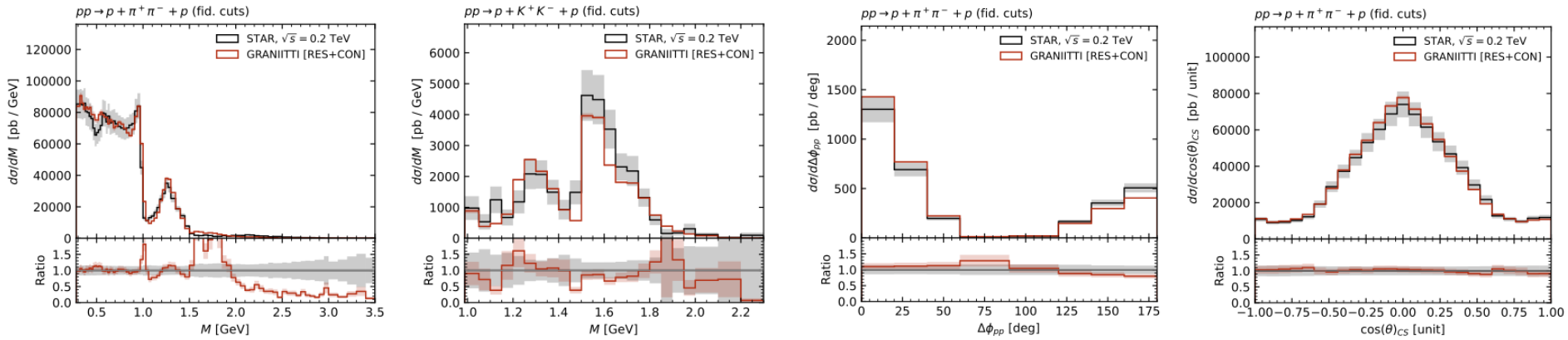


Fig. 4. The central system invariant mass in $\pi^+\pi^-$ (left) and K^+K^- (right).

Fig. 5. Forward proton $\Delta\phi_{pp}$ (left) and CS-frame angle $\cos(\theta)$ of π^+ (right).

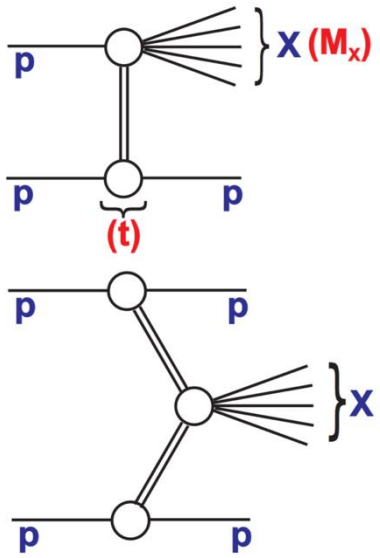
Good agreement with the tuned GRANIITTI Monte Carlo

Charged Particle Production at Midrapidity in SDD and CP at $\sqrt{s}$ = 200 GeV

Łukasz Fulek, PhD thesis AGH UST, arXiv:1906.04963

$$p + p \rightarrow p + X$$

$$p + p \rightarrow p + X + p$$



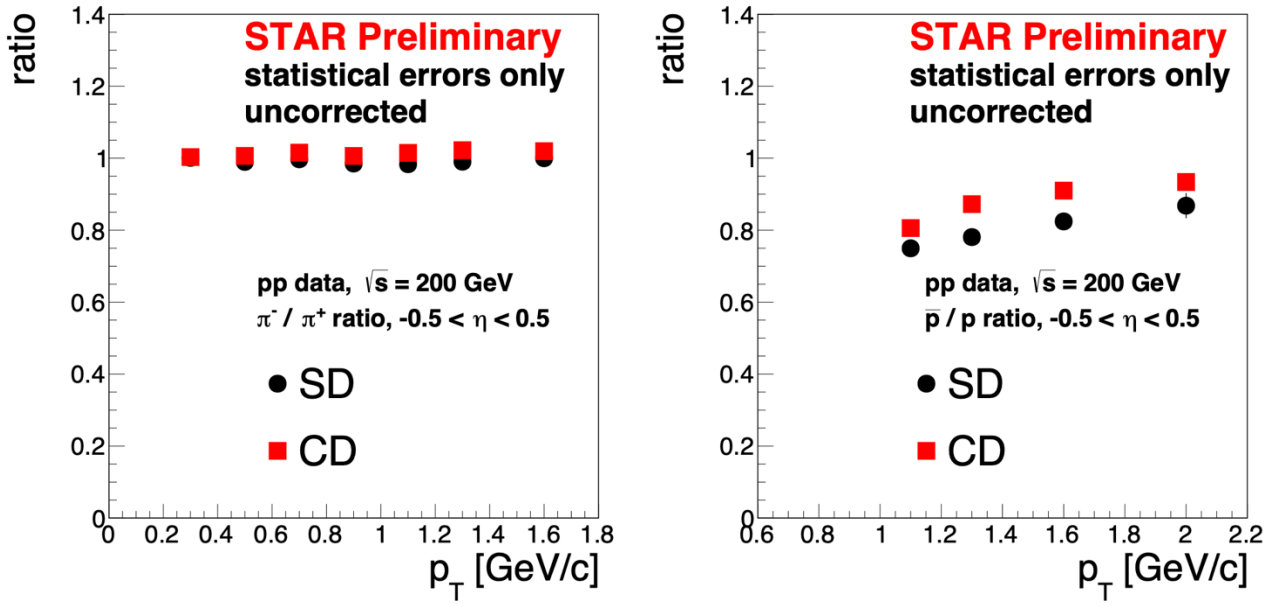
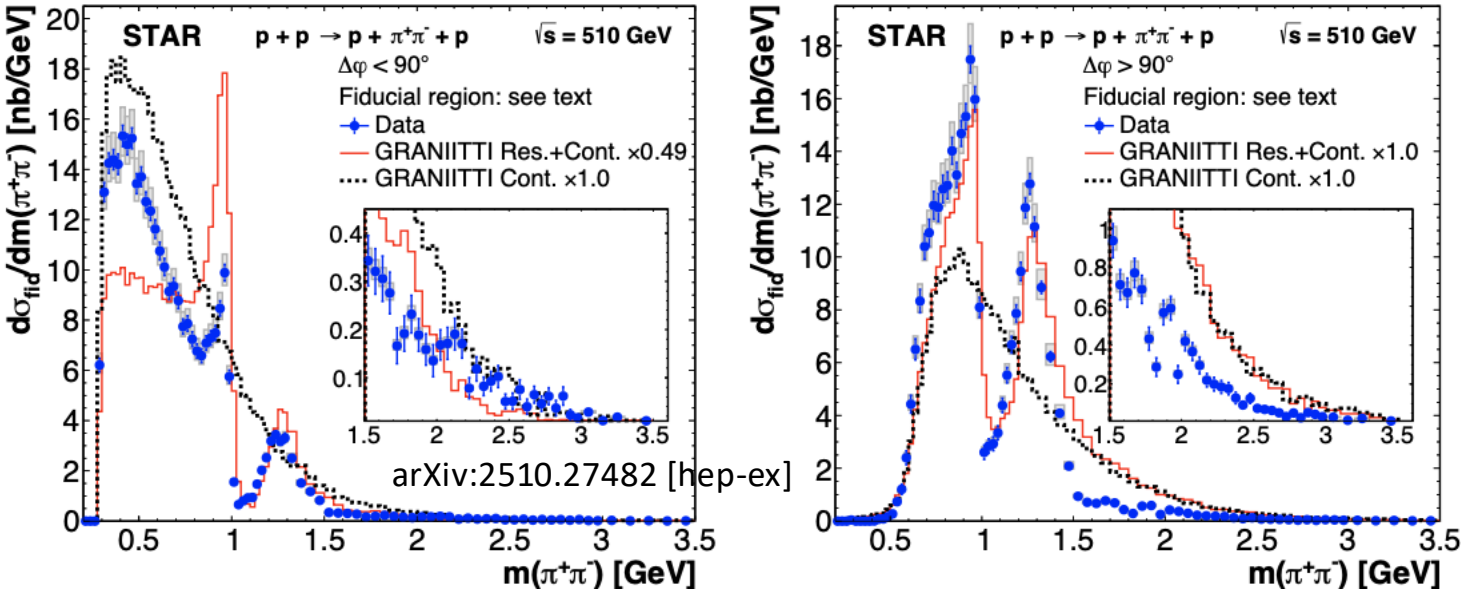


Fig. 5: Comparison of the π^-/π^+ (left) and $\bar{p}/p$ (right) ratios in $|\eta| < 0.5$ interval between CD and SD processes.

Results on CEP at $\sqrt{s} = 510$ GeV

T. Truhlar, PhD Thesis arXiv:2510.27482 [hep-ex] accepted to JHEP



arXiv:2510.27482 [hep-ex]

Features similar to those at $\sqrt{s}$ = 200 GeV are observed

Results on CEP at $\sqrt{s} = 510$ GeV

T. Truhlar, PhD Thesis arXiv:2510.27482 [hep-ex] accepted to JHEP

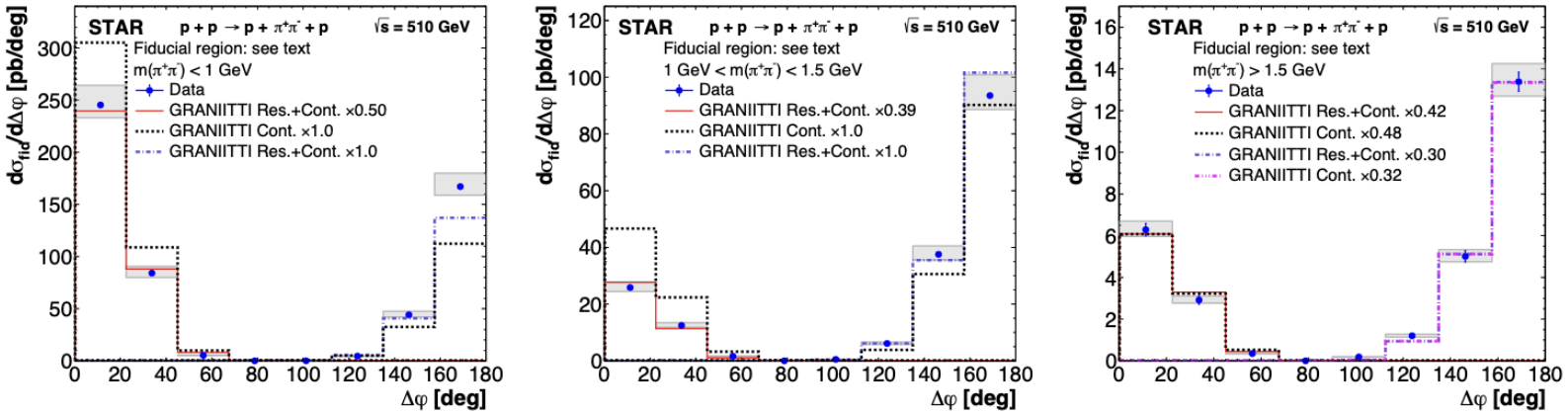
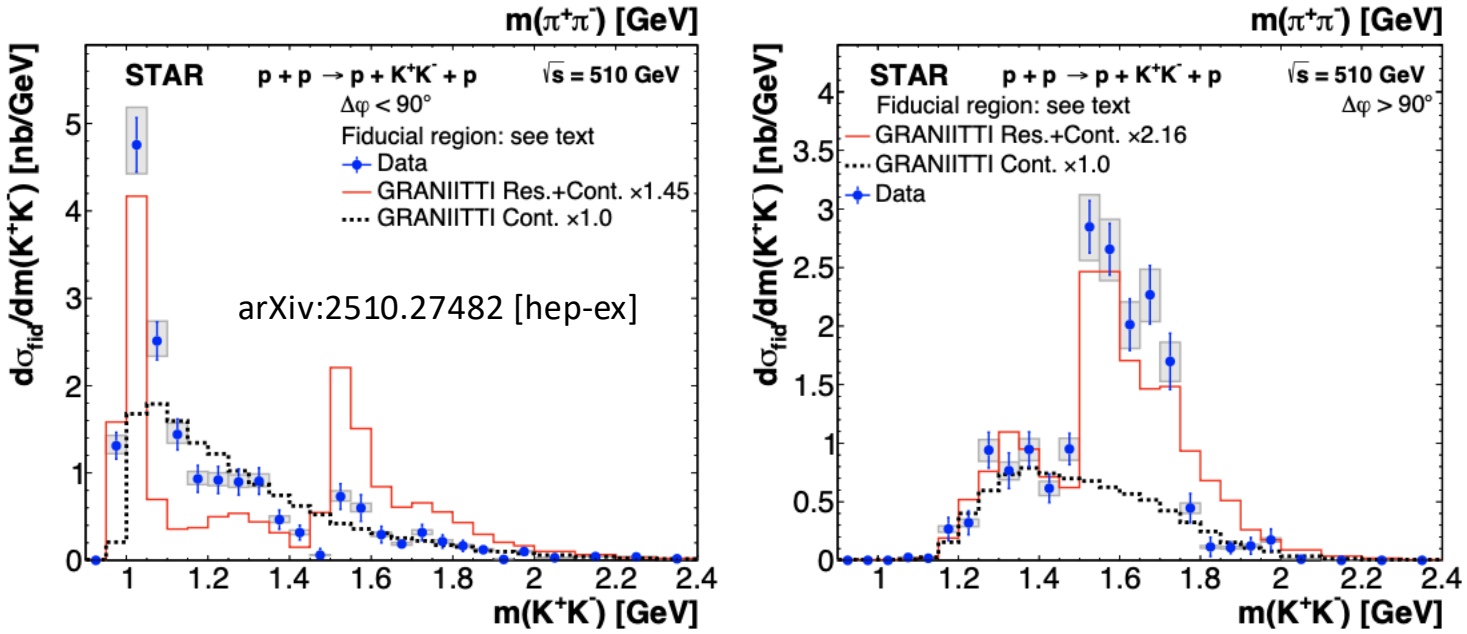


Figure 11. Differential fiducial cross sections of $\pi^+\pi^-$ pairs as a function of the difference in azimuthal angles $\Delta\varphi$ of the forward scattered protons in three ranges of the $\pi^+\pi^-$ pair invariant mass: $m(\pi^+\pi^-) < 1$ GeV (left), 1 GeV $< m(\pi^+\pi^-) < 1.5$ GeV (middle) and $m(\pi^+\pi^-) > 1.5$ GeV (right), measured in the fiducial volume explained in the text. Data are shown as solid blue points

Note asymmetry in $\Delta\phi$ as function of invariant mass

Results on CEP at $\sqrt{s} = 510$ GeV

Tomas Truhlar, PhD Thesis arXiv:2510.27482 [hep-ex] accepted to JHEP

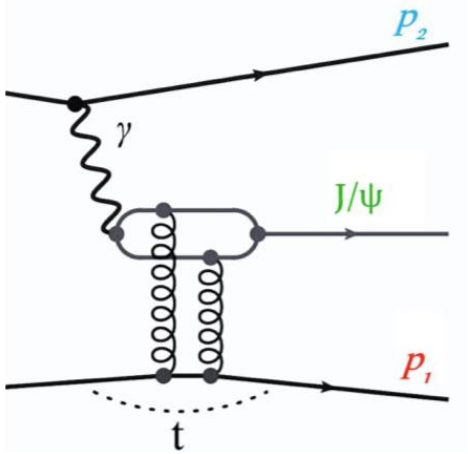


Peak at about 1 GeV observed for $\Delta\varphi < 90°$ also peak at about 1500 MeV

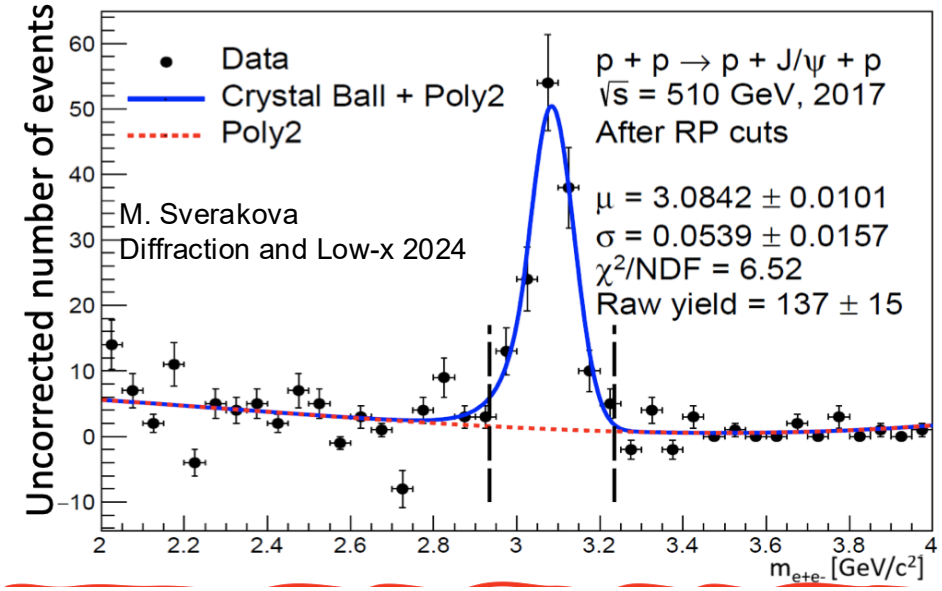
J/ψ Results at $\sqrt{s} = 510$ GeV

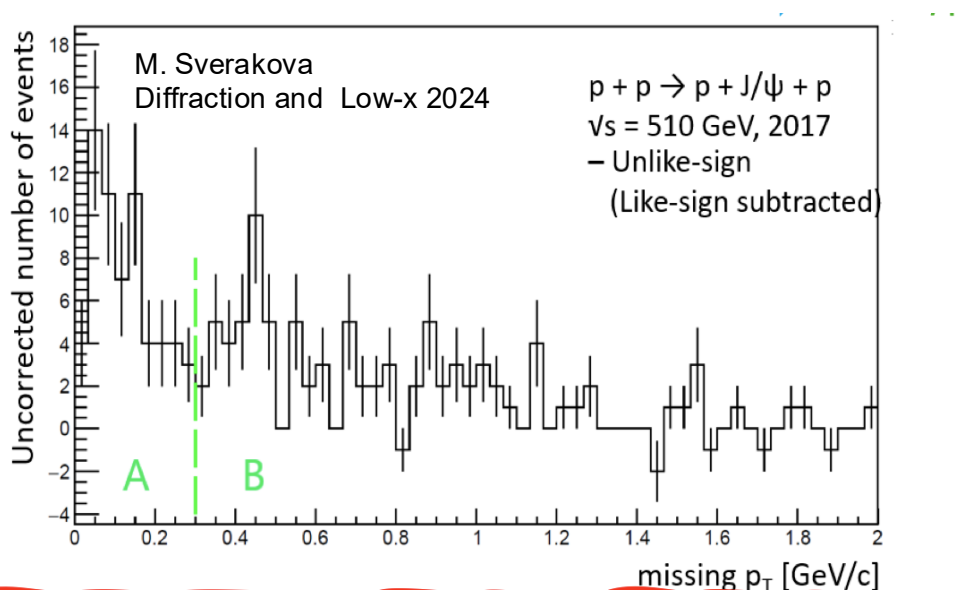
M. Sverakova Diffraction and Low-x 2024

- Prominent peak visible in the uncorrected invariant mass distribution
- Raw yield of J/ψ → e++ e- in p+p collisions with RP proton tagging extracted for the first time



- Peak near zero consistent with the exclusive process
- Broad structure from 0.3 GeV/c is consistent with non-exclusive processes





Summary I

1. The program with forward protons at RHIC delivered many important results in diffractive physics in pp collisions at $\sqrt{s} = 200$ GeV and $\sqrt{s} = 510$ GeV, which will input to phenomenological models in non-perturbative regime of QCD
2. This specialized program used unique features of the RHIC complex, including polarized proton beams.
3. What started as a stand-alone experiment evolved into a more comprehensive physics program with the STAR detector
4. There were three publications from the PP2PP experiment and five publications from the STAR experiment.
5. Five PhD theses and nine MSc theses written based on this program.

Summary II

Our results include:

- Total pp cross section at $\sqrt{s} = 200$ GeV
- Nonlinear exponential slope was found at $\sqrt{s} = 510$ GeV in pp elastic scattering
- Spin dependence of elastic scattering at $\sqrt{s} = 200$ GeV
- A very comprehensive study of CEP at at $\sqrt{s} = 200$ GeV and $\sqrt{s} = 510$ GeV
- A comprehensive study particle production in CP and SDD at $\sqrt{s} = 200$ GeV
- Possibility of diffractive J/ψ production measurement was demonstrated at $\sqrt{s} = 510$ GeV